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Dr F.B. Smith retires
Fifty years of dispersion
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In February 1992, Barry Smith retired from the Meteorological Office after an industrious 35-year career throughout which he made many valuable and distinctive scientific contributions, particularly in the fields of atmospheric dispersion and diffusion. Barry's interest in meteorology goes back to his school days when he set out his own meteorological station in his back garden and, when a 6th-former, he bought Sir Napier Shaw's *Manual of Meteorology*. Mathematical inclinations took him from Cheadle Hulme Grammar School to Manchester University where be obtained a first class honours degree in Mathematics in 1953. He remained at Manchester to undertake a PhD under Sir James Lighthill. This was a time of great interest and excitement in aerodynamics but, influenced by a desire to have some independence of Sir James, Barry chose a more meteorological area of work. Such an early manifestation of Barry's renowned independence will come as no surprise to those who know him!

On completing his PhD, Barry joined the Meteorological Office as a Junior Research Fellow at the Chemical Defence Establishment, Porton. In 1958 he became a permanent member of the Office as an SSO and made an energetic start publishing numerous papers including several in the *Quarterly Journal* of the Royal Meteorological Society. The topics varied from the 'analysis of observations of wind fluctuations' to 'the turbulent spread of clusters of particles'. In 1960 the Office sought to broaden his interests and he was sent to Stockholm for 7 months to learn from Dr Phillip Thompson about numerical weather prediction. On his return he worked on objective analysis and the

development of Lagrangian forecast models using the Mercury and then the newly installed KDF9 computers. Publications continued to flow, including one on the uncomfortable subject of 'The effect of advection in a region of no data'. Oceanographers take note! Later he joined Bob Murgatroyd to study stratospheric circulations. Barry's real interests however still lay in atmospheric diffusion and dispersion and it was no secret that he continued to spend time on such studies. In 1966 he persuaded the Office to allow him to spend a sabbatical year with Frank Gifford's group at Oak Ridge, Tennessee working on conditional dispersion theories and random-walk ideas. Thus began a close association between Barry and colleagues there, which still continues today. On his return, the Office made a final brief and unsuccessful attempt to divert his attention by posting him to work in the Geophysical Fluid Dynamics Branch. However, Barry's persistence and the Office's recognition of his talents prevailed and from 1967 until his retirement he has been a mainstay of the boundary layer branch. At first he was deputy to Frank Pasquill and in 1974 he became Head of the Branch. Barry's distinctive approach to the in-tray was always to deal efficiently with items he felt important, but to leave other actions either forever or until the third demand. He was also not one to waste time on staff who were obviously getting on with useful work but was always generous with his time in giving help and direction where needed. Close colleagues generally approved of this regime. In spite of the frustration it may have caused senior management at times, one distinct benefit of Barry's individualistic administrative style was his continuing high scientific productivity. This was duly recognized in 1979 on his transfer to an Individual Merit Research post, with a highly deserved promotion in the same capacity to grade 5 in 1986.

Barry's initial contributions to the understanding of atmospheric dispersion were often idealized and involving 'heavy' mathematics. Although he never abandoned such sophistication, the hallmarks of Barry's activities in the last 20 years have been his ability and willingness to tackle real problems and his solutions in the form of practical tools for, as he would say, 'the man in the field'. In many instances, he has converted pages of equations into simple curves and formulae. In particular, the nomograms and overlays which form the basis of the Office's chemical emergency response are due to him. The use of these practical schemes has also been assisted by Barry's skill as a teacher and lecturer. He is known for well-prepared public talks and lecture courses with good diagrams which are easy to follow and capture the essential points.

In 1983, his long-standing collaboration with Frank Pasquill was suitably crowned with their joint authorship of the third edition of the recognized seminal test *Atmospheric Diffusion*. Barry's interests were not confined to short-range dispersion and during the 1970s he became involved in the study of long-range transport in connection with acid rain. This involved studies of synoptic-scale air trajectories and the verification of his models for the transport and deposition of atmospheric pollutants with field studies of marked power-station plumes sampled by the MRF C-130 aircraft. In typical fashion he became involved in the whole problem, from the emissions and the atmospheric dispersion to the atmospheric chemistry and the deposition processes. As a leading European expert on acid rain his impartial advice and scientific integrity were widely sought after on national committees and in international fora. His contributions were recognized in 1981 by the award of the FitzRoy Prize of the Royal Meteorological Society. During the Chernobyl accident in 1986 he was again at the heart of the Office's advice to Government. Subsequently, he undertook a careful and thorough analysis of the meteorological factors which governed the spread of the plume from Chernobyl and the eventual deposition of its radioactive material. Then together with Roy Maryon he helped respond to the Cabinet Office request for an operational system to provide detailed predictions of the transport and deposition of radioactive material that might arise from any future similar accident. The resulting nuclear accident model, NAME, is one of the best of its kind available. The model and Barry's expertise were put to good use in investigating the impact of the oil fires started in the recent Gulf War.

Barry's interests and contributions have by no means been confined to his professional efforts in the Office. Almost simultaneous with the start of his Office career has been his devotion to the Scout Association, in particular the Cub Section. In this context, Barry's exploits are legendary and, not surprisingly, his unique and unstinting efforts have been fully recognized by the Association which has honoured him with medals for his outstanding contributions. Over the years, many colleagues have been charmed or press-ganged by Barry to aid and abet him at Scout functions. In the process, all will have witnessed the unique brand of fun, excitement, encouragement, guidance and education that Barry has provided and continues to provide, for those Cubs privileged to have him as their 'Akela'. His remarkable success with Cubs is undoubtedly linked to his open approachability, friendliness and good humour, which his colleagues in the Office have long appreciated. Although the Met. Office has lost a true expert of high international repute, Barry will continue at large to contribute to the subject. He has accepted positions as an Honorary Professor at the University of East Anglia and as a Visiting Professor at the Centre for Environmental Technology at Imperial College, London, as well as retaining a number of other commitments. Noting the volume of material transferred from his office to his home, both must be at risk of settlement damage. All his colleagues will surely wish him a long and rewarding retirement.

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The first 50 years in the study of atmospheric dispersion

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Before 1914, the Meteorological Office was small and dedicated to the task of making meteorological measurements, drawing charts and issuing forecasts. At the beginning of the World War I, the Office contained only about six professional meteorologists, who had learned their trade in the hard school of experience, and another half a dozen young men from the universities who were at the beginning of their careers.

The geostrophic wind, regarded for over 70 years as a mere theoretical curiosity of an impressionable Frenchman, G. Coriolis in 1835, was still hardly recognized as a practical tool of the working forecaster. However in 1919 Sir Napier Shaw, in the preface to Part IV of his *Manual of Meteorology*, wrote 'Within the past four years..... we have found a guiding principle of great practical utility in the relation of the wind to the distribution of pressure...in the free atmosphere which follows very closely the laws of motion under balanced forces depending on the spin of the earth'.

Nevertheless, the basic ideas of wind structure and turbulence were already under investigation. The idea of a momentum exchange coefficient had been proposed by Boussinesq. The idea was then developed by Schmidt in Germany who called it an austausch coefficient (although his work was not properly written up until 1925), and in 1902 Ekman had published his famous paper on the establishment of ocean currents due to wind stress, which when applied to meteorology led to the Ekman spiral of wind in the boundary layer.

The German school had thus developed some major ideas about turbulence, although it was in Britain where scientists like Reynolds had already established several fundamental concepts. In two papers in 1883 and 1884, Osborne Reynolds explained the conditions in which streamline motion would break down into turbulent motion; it depended on whether or not the velocity V of the fluid was sufficiently high that Vl/v exceeded some critical value of the order of 2000 (where l is the linear dimension of the system and v is the kinematic viscosity). He noted that whereas streamline motion could be described by the use of hydrodynamical equations, turbulent motion has to be treated statistically like the motion of gas molecules. Rayleigh in a Report to the Advisory Committee for Aeronautics (1909–1910) had already set out the principles of dynamical similarity.

Before World War I, G.I. Taylor had been appointed the Schuster Reader at the University of Cambridge. Following the tragic loss of the *Titanic* in the western Atlantic after striking an iceberg in 1912, the government fitted out an old wooden sailing ship, the *Scotia* to look for icebergs in the North Atlantic and to report their positions by the new radio method. Taylor was on of three scientists appointed to accompany the expedition. He decided to study the vertical transfer of heat and momentum and water vapour in the friction layer of the air. He arranged for instrument-carrying kites and balloons to be flown from the ship. He measured wind, temperatures and humidity profiles up to about 2500 m on several occasions. He also needed information of the previous history of the air mass and this he was able to infer from records of water and air temperature and wind data collected by ships upwind of *Scotia*. In a 1915 paper, Taylor gave a rational description of the profiles in terms of the upwind history of the air and a supposed 'eddy conductivity' and a 'mixing length' (defined as the vertical distance over which an element of fluid and its vorticity would move before attaining the same value as its surroundings and losing its identity). Unknowingly his concept of mixing length was similar to that of Prandtl ten years earlier, although Prandtl had thought in terms of momentum rather than vorticity.

Taylor also analysed the approach of the wind to the geostrophic at the top of the boundary layer, showing good agreement between theory and observations. Again he was unaware of the earlier work of Ekman. Taylor however used the better lower boundary condition of assuming stress and wind to be parallel at the surface.

In 1914, Taylor investigated stability. He inferred that an airflow is stable to small disturbances provided:

$$\left(\frac{\mathrm{d}U}{\mathrm{d}z}\right)^2 < \frac{4g\Delta\rho}{\rho L}$$

where $\Delta\rho$ is the drop in density over a layer of vertical thickness L. This work was part of an essay 'Turbulent motion in fluids' which won him the Adams Prize of the University in 1915.

In the same year, G.I. Taylor joined a group of civilians at Farnborough working for the Royal Flying Corps helping to put the design and operation of aeroplanes on a scientific basis. He felt the need to be able to fly aircraft to do his work properly, so unable to do this as a civilian he enlisted and later attained the rank of Major. On 14 February 1916 he became the Professor of Meteorology to the Royal Flying Corps (RFC), attached to the Meteorological Office, but much of his work continued to be concerned with the proper

design of aircraft and the study of the flow of air over wings and the resulting pressure distribution. Eventually he left Farnborough in 1917 to concentrate on more meteorological issues for the RFC although little in the way of research into dispersion resulted during the next few years. Before doing so, however, Major Taylor had constructed a sophisticated anemometer which could measure wind speed and its fluctuations in three dimensions. This was set up on a chimney at Pyestock to test the diurnal variation of gustiness.

However it wasn't until 1915 that attention in the Meteorological Office was first directed towards diffusion. This resulted from the use of poisonous gas in the front line. It was first used by the Germans against the Algerian Division of the French Army at Ypres on 22 April 1915 by the simultaneous discharge of chlorine from 6000 emplaced cylinders over a front of about 4 miles. The effects were dramatic; those who could, fled the front line and the front collapsed. On 24 April the 2nd Canadian Brigade was also attacked in this way. British troops were first attacked with gas on 1 May. Army Chiefs requested urgent action and help. The first proper gas-mask was designed in the following August and an Establishment was set up at Porton in 1916 with a Meteorological Station in support. The head of the station was Corporal T.A. Beardsmore, B.Sc., RE, whose responsibility was to make extra meteorological measurements during smoke releases as well as routine meteorological observations. They soon found that experiments were most successful in winds less than 7 m.p.h. and when ground temperatures were lower than the air temperatures (i.e. in stable conditions). The small station came under the direction of Colonel H.G. Lyons who was stationed at a Home Unit on Salisbury Plain (possibly Larkhill).

Their routine work of attending experiments and making standard meteorological observations took up most of their time. One of these experiments concerned the production of smoke screens under widely varying atmospheric conditions and at different ranges. However they did find time to investigate:

(a) The variation of wind with height, and
(b) The eddies and currents of wind in the immediate vicinity of woods.

From May 1916 onwards, field trials were carried out with many liquified gases to determine, amongst other things, how the gas cloud travelled and the effects of ground and air temperatures, ground contours, winds, etc. on the resulting concentrations.

Going back in time just a little, Britain first used gas against the enemy at Loos on 25 September 1915. The meteorologist commissioned to forecast when conditions would be suitable was Capt. Gold. On the 24th the winds were very light, but with observations from the Western Front and from Britain he predicted the wind would turn to the west-south-west and would therefore be suitable for a release. The winds however remained very light and Gold was greatly relieved when reports began to come in of gas rolling towards the enemy lines.

In 1917 an Advisory Committee on Atmospheric Pollution was established at the request of the Department of Scientific and Industrial Research (DSIR) under Sir Napier Shaw. This came under the control of the Meteorological Office in 1919 and remained so until, in 1928, it came under the chairmanship of Warren Spring Laboratory. The objective of the Committee was largely to study levels of pollution in urban areas in collaboration with local Councils. A network of gauges was established to record the levels of smoke.

It is about this time that L.F. Richardson had completed his pioneering work on numerical weather prediction (NWP) whilst serving as an ambulance man at the front. I believe at one stage he temporarily lost his manuscript and calculations in a muddy trench! In 1918 he was out of the war and was stationed in the Meteorological Office Observatory at Eskdalemuir. However he did not stay there long and was soon moved to Benson where W.H. Dines was working on upper winds. Richardson then found time to submit his work on NWP; a paper described by others as 'elaborate'! The paper was sent to the Royal Society where it was published.

He devised a method of measuring the wind at different levels by its differential effect on steel spheres shot nearly vertically upwards so that when they returned to earth the displacement could be noted. The spheres varied in size from a pea to a cherry, and the system was particularly useful in fog or cloud when visual observations of a balloon could not be made. However the system had its dangers, and it was ultimately abandoned mainly because with spheres of a non-lethal size and muzzle velocities below the speed of sound the height reached was not great enough to satisfy the synoptic meteorologist. (But how about it, Cardington 1992?!)

Richardson in 1919 took up G.I. Taylor's idea of eddy conductivity and coined the term 'eddy diffusivity' for K. He showed that K derived from observations of smoke and thistledown and dandeliondown across different types of land surface, of steamer smoke at sea and of the growth of cumulus clouds, varied from 5 to 10^6 cm^2 sec^{-1}), much more widely than had previously been supposed. In 1920 he published his famous work on the Richardson Number the criterion for deciding whether or not turbulence levels will increase or decrease, given gradients of wind and temperature.

Meanwhile Alcock and Brown had flown the Atlantic for the first time on 14/15 July 1919, and David Brunt had been appointed the Superintendent of the Met. Establishments for the Army (including Porton). Brunt was stationed at Shoeburyness. Up to 31 March 1920, no action had been taken to provide civilian meteorological staff at Porton, since its future programme of research, if any, was uncertain, but after Sir Napier

Shaw resigned as Director of the Office and Dr G.C. Simpson took his place, civilians were sanctioned by the Treasury with N.K. Johnson as the Station's Head. In 1921 the Chemical Defence Establishment at Porton was officially opened with Nelson Johnson as Superintendent of the 'Meteorological Department'. The Department's duties were to carry out research into meteorological problems arising in chemical warfare, and to provide meteorological information to the Establishment as a whole.

G.I. Taylor, now back at Cambridge, carried out a short but crucial study of the relationship between dispersion and turbulent fluctuations which led to the classical formula:

$$\sigma_y^2 = 2\sigma_v^2 \int_0^T \int_0^t R(s)\,ds\,dt.$$

The work was published in the London Mathematical Society in 1921 but it was not until the 1930s that O.G. Sutton took up the method again and applied it to dispersion in the boundary layer, and that the method was applied to laboratory flows by Taylor himself.

At Porton the next few years seem rather quiet, but in reality the staff there were grappling with the problems of measuring velocity and temperature gradients in the lower atmosphere and in carrying out some formative dispersion experiments. In any case, the number of staff in the Met. Department was rather too low to carry out any very extensive work during this period.

In 1923 smoke experiments indicated that at 100 m downwind from the source the width of the cloud, defined by one-tenth peak concentration, averaged about 35 m in neutral conditions for a release duration of 4 minutes but values ranging from 23 m to 47 m were found. R.F. Budden analysed the form of the cross-wind concentration distribution and showed that

$$C(y) = C(0) \exp(-ay^{1.5}),$$

at variance with the Gaussian form, which had been expected. This lower exponent (1.5 rather than 2) was broadly confirmed later in 1931 by E.L. Davies at Cardington.

The staff also endeavoured to measure vertical dispersion. They did this by spacing a number of smoke candles some 4 m apart across-wind and sampling the smoke at various heights on a downwind tower using a hand-pump. The candles were of a pitch composition and the downwind concentrations were inferred by the 'stain-meter' technique devised by Scrase in which the smoke was drawn through a filter and the resulting stain compared with a set of standard stains corresponding to different concentrations. The results implied an average plume-top height of 10 m at a range of 100 m in neutral conditions. These results were later used by Sutton in the 1930s to validate his new diffusion formulation.

In 1922 a name that later became associated with airship meteorology came on to the scene. This was M.A. Giblett, who worked on and published a paper on evaporation from large expanses of water.

In 1925 the Met. Department was strengthened to include not only N.K. Johnson, but E.L. Davies, F.J. Scrase and O.F.T. Roberts. By the following year they had produced an interesting paper entitled *The measurement of the lapse rate of temperature by an optical method*. The team also carried out further dispersion experiments extending the range of travel to 300 m and 1000 m. They showed amongst other things that in neutral conditions the cloud-width varied roughly like $x^{0.8}$.

In the years up to and including 1925, there was considerable interest in the potential of airship travel. In 1925 an Airships Division was set up at the Pulham Airship Station under L.G. Garbett to provide meteorological information. The first major flight was made which was from England to India via Egypt in the R33. A year later a separate Airships Met. Division was established at Cardington under M.A. Giblett as Superintendent. One of their first tasks was to investigate short-period fluctuations of wind speed and direction. They also worked on the horizontal scale of eddies, especially in very strong winds. To this end they set up a network of anemometers. In 1928 this network was modified to three anemometers at the corners of an equilateral triangle of side 700 ft (roughly the dimension of an airship) with a fourth anemometer at the centre.

In 1929 Cardington staff were charged with predicting conditions when it was safe to move the airship from its hangar to the launch-mast, the conditions at the mast itself and to issue warnings of any sudden changes in wind, and to make forecasts of weather along the route.

On 4 October 1930, the R101 set off for India with Mr Giblett on board as Met. Officer. The terrible disaster that followed led to his death and to the end of airship development using hydrogen.

Going back to 1926 we can pick up again developments in the study of dispersion. L.F. Richardson, as noted earlier, had inferred the very wide range of eddy diffusivities appropriate to the diffusion equation on different scales. Richardson recognized the different nature of relative diffusion. He defined a distance-neighbour function q(r) defined as

$$q(r) = \frac{1}{Q} \int_{-\infty}^{\infty} C(x)C(x+r)\,dx$$

where $C(x)$ is the concentration of x, Q is the total number of particles. He proved that if the diffusion was Fickian then q satisfied

$$\frac{\partial q}{\partial t} = 2K \frac{\partial^2 q}{\partial r^2}.$$

In non-Fickian diffusion he suggested replacing $2K$ by $F(r)$ so that

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial r}\left(F(r)\frac{\partial q}{\partial r}\right).$$

Using the data from different scales including the balloon data described below he inferred $F(r) = 0.6r^{4/3}$ for values of r between 1 m and 10 km. For objects floating on the surface of the sea however, the coefficient 0.6 should be replaced by 0.035, sixteen times less or in the same ratio as the viscosity of air to that of water.

Richardson decided to collect as much longer-range dispersion data as he could. However much of these were rather crude and heterogeneous. His balloon data were obtained largely from balloon competitions organized at Brighton and in Regent's Park, London. He and Proctor found agreement with the 4/3 law given above but that if the data were subdivided into wind-speed classes then $K \propto \sigma^{5/3}$ where σ was the standard deviation of balloons from their mean track. It is important to remember in interpreting this result in terms of relative diffusion that some of the release durations extended over about 10 hours.

In 1929 O.G. Sutton joined the Porton Group and launched a new development of the work there on dispersion which lasted throughout the 1930s. During this time a number of (later famous) scientists joined him: F.J. Scrase, A.C. Best, P.A. Sheppard, K.L. Calder, F. Pasquill and C.H.B. Priestley.

The idea of a constant eddy diffusivity K led to the dimensions of a plume expanding as $x^{1/2}$, but field data showed that this was not generally the case. In the vertical it was generally accepted that K could be made a function of height, reflecting the change in the nature of turbulence as z increases. But it was harder to resolve the problem for horizontal dispersion. As we have already seen, Richardson had thrown some light on this problem but it really remained unresolved. Sutton saw the urgent need for a different approach. He decided to combine Taylor's 1921 statistical theory with the old concept of mixing length. He searched for an appropriate form for $R(s)$. On intuitive and dimensional grounds he suggested in 1934:

$$R(s) = \left(\frac{v}{v + \sigma^2 s}\right)^n$$

where v is the kinematic viscosity and n is a constant to be identified.

The essential equations are

$$K = \overline{w'^2}\int_0^{t_0} R(s)\,ds$$

where t_0 is the time for the correlation to fall to effectively zero. Thus

$$K = \frac{v^n}{1-n}(\overline{w'^2}t_0)^{1-n}.$$

Then with

$$t_0 = l/|\overline{w'}| = |du/dz|^{-1}$$

and

$$l = k|du/dz|/|d^2u/dz^2|$$

and the assumption of a Gaussian distribution in w'

(hence $\overline{w'^2} = \frac{1}{2}\pi|\overline{w'}|^2$)

$$K = \frac{(\pi k^2/2)^{1-n}}{1-n} v^n (|du/dz|^3 |d^2u/dz^2|^{-2})^{1-n}.$$

If we then assume that the shearing stress τ is changing only very slowly with height so that $K\,du/dz$ is effectively constant, and that we have a power-law wind profile then

$$u \propto z^{n/(2-n)}$$

and we can then determine n from the shape of the wind profile. It follows, using Taylor's equation for the σ's that

$$\sigma_x^2 = \frac{1}{2}C^2(uT)^{2-n}$$

where T is the time of travel and C is given by

$$C^2 = \frac{4v^n}{(1-n)(2-n)u^n}\left(\frac{\overline{u'^2}}{u^2}\right)^{1-n}.$$

Similar expressions apply for σ_y and σ_z. These values of σ can then be inserted into a Gaussian plume formulation to obtain the concentration distribution.

Despite the success with small-scale boundary-layer studies of vertical transfer, Sutton's form of K-theory ran into difficulties when tested against observations of the vertical diffusion of smoke in the field. It gradually became clear that the significance of surface roughness had not been fully appreciated. Calder and Sheppard were tasked with trying to sort out the problem. Over aerodynamically rough surfaces it proved necessary to replace v by $u_* z_0$ where u_* is the friction velocity and z_0 the roughness length. Thus v was replaced by a macro-viscosity. Experimentally the value of n was found to be about ¼ in near neutral conditions.

During much of the 1930s, Sutton's formulation was further developed and much effort was expended in exploring the profiles of wind (and temperature) in more detail to obtain optimum values of n in different conditions. I have rather laboured Sutton's approach because it dominated thinking about dispersion for over 20 years in this country.

In 1931 and 1934 Porton staff carried out further dispersion experiments out in the field at Cardington. To their surprise they found that plume widths over similar sampling durations were greater at Cardington

than at Porton even though the general lie of the land was flatter at Cardington.

In 1934 the experiments were accompanied by measurements of turbulence (using a bi-directional vane) which showed that the width of the trace of directional fluctuations compared well with the plume width. They also displayed a close relation between cloud-width and atmospheric stability as indicated by the Richardson Number.

1935 saw the return of G.I. Taylor to our story. In that year he extended his initial 1921 analysis in which he regarded the changes in velocity of a particle as a continuous process by applying the same concept of continuous change to the Eulerian description of the spatial structure of turbulence. In this he defined a length-scale of turbulence as the integral of the space-correlation of turbulent velocities, recognizing that the scale could well be different in the three component directions.

In 1938 Taylor adopted the 'frozen-eddy' concept which related the spatial correlation alongwind to the temporal correlation at a fixed point,

$$R(t) = R(x)$$

when $x = ut$. He also introduced into turbulence theory the relation between the correlation coefficient and the spectrum of turbulence through the Fourier integral. The practical importance of this was that it brings out the idea of a continuous range of eddy sizes and helps to identify those eddy sizes which are of most significance as regards kinetic energy and those which are of most importance in creating dispersion. It was these ideas that were later developed first by A.N. Kolmogoroff in the USSR in 1941, and later by G.K. Batchelor in and after 1946 and subsequently by many others.

Frank Pasquill joined the team at Porton in 1937, two years before the outbreak of war. He was given the job of investigating dispersion over the sea. By the beginning of 1939 he had everything organized to measure the profiles of wind, temperature and humidity using equipment sited on a landing-stage at Bognor. After just a few trials, the approaching threat of war changed the priorities and he was told to concentrate on problems of the evaporation and persistence of mustard gas on the ground back at Porton. Sutton had developed a theory for evaporation along the lines outlined earlier. This theory was extended by Calder to give the absolute rate of evaporation. Pasquill was asked to test this using a large wind-tunnel specially built at Porton for this purpose. He showed that the evaporation rate could be well predicted using Sutton and Calder's treatment by knowing the power-law variation of wind with height in the shallow boundary layer over the wind-tunnel floor. The war had, of course, a profound effect on the programme of work at Porton. In 1943 following the disastrous advance of Japanese troops across south-east Asia, the Government feared that chemical warfare might be used by the Japanese in the hot, humid conditions of the tropics, for example in Burma. Uncertain of their possible behaviour, they sent a team out to north Queensland to carry out tests. Pasquill was included in the team as the meteorologist. The role was mainly support, with little chance to do research.

At the end of the war, in 1946, Pasquill returned to the United Kingdom and found himself posted to the School of Agriculture at Cambridge where he again worked on the determination of profiles and evaporation. He was able to show that the eddy diffusivity for water vapour was very close to that of momentum, and that the von Kármán constant was likewise the same as that for momentum, namely 0.4. In 1949, he agreed to be seconded to the Atomic Energy Authority at the Harwell Laboratories. He became involved in studying the distribution of radioactivity in the countryside around Harwell originating from one of the reactors on site. He also took up the work started by C.S. Durst in the Office on the long-range travel of radioactive material both from atomic bomb tests and from nuclear plants on a global scale. In shorter-range studies Pasquill and Crabtree were able to fit small smoke-generators on to the cable of a captive balloon. Individual puffs could be followed for quite some distance downwind. The striking thing which they noted was that the track of an individual puff was surprisingly straight even though there were quite big changes in the wind at the source, implying that the Lagrangian time-scale was much longer than the Eulerian scale.

Meanwhile Calder and Sheppard continued after the war to work on problems of evaporation from aerodynamically rough surfaces as well as from water surfaces. Batchelor was extending the spectral work initiated by Taylor and by Kolmogoroff. In 1950 he had published a paper on the application of Similarity Theory of turbulence to atmospheric diffusion. A big landmark came on the publication of his monograph *The theory of homogeneous turbulence* in 1953 which set out in a coherent way all the new advances in homogeneous turbulence as viewed through these spectral and correlation statistical methods. This laid the way for further advances in dispersion theory which came later in the decade and beyond.

After 1950 the number of scientists working in the study of dispersion began to increase, slowly at first but with ever increasing speed. Highly productive groups became established in the USA at Penn State University under Panofsky, at Oak Ridge under Frank Gifford, and at the Environmental Protection Agency under Ken Calder (who had emigrated in 1949) and other; other groups started in Japan, in Germany, at Roskilde in Denmark, in Sweden and, of course, in the Soviet Union. To tell the story from this point would require many books, suffice it to concentrate on progress in the United Kingdom and at Porton in particular.

In 1954 Pasquill returned to Porton, replacing C.J.M.

Aanensen who in turn had replaced Calder. Aanensen had worked on the diffusion of gases in cities, using the large wind-tunnel to carry out his experiments. He had also been contemplating the use of a new tracer for longer-range dispersion experiments. Pasquill took up this project. One of the key factors in the work at Porton in the next few years was the application of these new methods for evaluating dispersion. New tracers were employed that were easier and more accurate than some of the older methods. The first new tracer was zinc cadmium sulphide which, when released as a fine powder, could be collected on sticky plates and the particles counted subsequently in the laboratory since they fluoresced under ultra-violet light. Another tracer was lycopodium spores that were collected on sticky cylinders and could be counted under a microscope. These enabled dispersion experiments to be carried out to 100 km or more, although many were at much shorter range. J.S. Hay did much to make these tracer techniques practical and effective. One interest was in the longer-range travel of cloud seeding agents (like silver iodide) which could diffuse up into cloud, from generators on the ground, and hopefully enhance rainfall rates. The tests that were carried out had to be done in situations of otherwise rather uniform rainfall so that the effects, if any, could be observed. Unfortunately, since such uniform conditions could only be expected with warm fronts, the silver iodide found it very difficult to penetrate the rather stable inversion at the frontal surface so that little got into the precipitating cloud. The experiments turned out to be rather a failure for this reason.

Another great aid to better field-studies came with the development of much more sensitive and useful instrumentation in which J.I.P. Jones played such an important role. The dispersion work that Pasquill and Crabtree had done at Harwell, and the subsequent studies made at Porton led to the useful concept that the Lagrangian spectrum of turbulence, required to predict dispersion, could be well estimated from the Eulerian spectrum (measurable using fixed anemometers) by assuming the two had the same shape but the Lagrangian spectrum was displaced towards lower frequencies.

F.B. Smith joined the group in 1956. He extended the range of analytical solutions of the diffusion equation then available with u and K profiles more in line with measured profiles through the boundary layer. He was also able to include the effects of dry deposition into some of the these solutions. He was attracted by the possible application of Monte Carlo techniques to atmospheric dispersion but was largely thwarted in this by the lack of computer facilities which did not become available until the early 1960s.

He also obtained the first solutions for dispersion in convective conditions in which thermals and compensating downward subsidence in the air produced concentration distributions in the vertical radically different from those obtained by simple K-theory but much more in line with those observed in the real atmosphere.

Towards the end of the 1950s, Smith presented the results of a theoretical study into the turbulent growth of puffs of heavy particles falling from their release point towards the ground. This was based very much on the extension of Taylor's statistical approach to dispersion and his work on the spectrum of turbulence. Smith and Hay later extended this work to puffs of passive particles, showing that the growth rate accelerates initially as the puff grows but asymptotically approaches the growth rate of a plume from a continuous source. He showed the growth rate could be expressed in terms of an integral of the energy spectrum weighted by a simple factor dependent on the puff size.

Pasquill had been approached in 1958 by the UK Atomic Energy Authority following the Windscale accident for current methods of estimating dispersion using easily obtained meteorological data. Pasquill realized there were no such simple methods. However, an important field experiment had been carried out in Nebraska in the USA called 'Prairie Grass'. The results complemented the results of the Porton experiments, extending these both in terms of range and in the effects of thermal stratification. Grouping all the results together it was possible to associate different rates of vertical dispersion with broad classes of wind speed and incoming solar radiation, or insolation, subjectively assessed, using cloud cover as a guide. He defined six categories of stability called A, B, ..., F. A was the most unstable category to be found only in light winds and strong insolation. Category D was for 'neutral' conditions, most commonly found in overcast conditions with winds above $5\ m\ s^{-1}$. At night, cloud amount replaced insolation as one of the key factors. The most stable category was F which occurred when there was little or no cloud and the winds were light. However, Pasquill's original scheme did not include any guidance at night when the wind speed fell below $2\ m\ s^{-1}$, although later versions associated this state with an even more stable category G. Pasquill provided curves of plume depth with range from the source for each of his six categories. In conjunction with the assumption of an approximately Gaussian profile shape, calculations of downwind concentration became extremely simple. Pasquill emphasized that his scheme was only to be used if wind fluctuation data were unavailable and only for near-ground-level sources.

The scheme was published in 1961 in the *Meteorological Magazine* and with some extensions suggested by Gifford it soon became the accepted method to use, and is still a valuable tool, extensively used, even in 1992.

With the onset of computers, new experimental and theoretical advances would soon become possible, but that is another story. The year 1960 really marks the end of an interesting 50-year initial development of a subject that has not ceased to be of considerable importance.

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Low wind-speed meteorology

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Summary

Low wind-speed conditions are particularly important for the science of air pollution because it is under these conditions that the highest ground-level concentrations are often experienced, and because the state of the lower atmosphere is often least well defined and predictable. Furthermore, most of the conventional models for dispersion are to some extent suspect because of their assumptions when the wind speed falls below about 2 m s^{-1}. This paper explores the meteorological nature of low-wind conditions, and thereby emphasizes many of the difficulties associated with this state.

1. Definition of low wind-speed conditions

1.1 Wind speed less than turbulent velocities

One useful definition of low wind speeds is that the mean wind speed (defined over some specified time interval) is comparable or less than the root-mean-square turbulent horizontal velocity, σ_u. In unstable conditions, the magnitude of σ_u can be defined in terms of the friction velocity u_* and the sensible heat flux H

$$\sigma_u^2 = 0.3w_*^2 + 6.25u_*^2$$

where w_* is the convective velocity

$$w_* = \left(\frac{gHh}{\rho C_p T}\right)^{1/3}$$

and h is the height of the boundary layer, which in many conditions can be approximated for in this calculation by 1000 m. C_p is the specific heat at constant pressure and ρ is the air density.

The friction velocity can be calculated using Monin–Obukhov similarity theory in terms of the measured wind at 10 m, the heat flux H, and the surface roughness z_0. Such a calculation is implicit in Table I where values of σ_u are given for different values of u (10 m) and heat flux H.

Table I. σ_u (m s^{-1}) for $z_0 = 0.01$ m in unstable conditions, with different values of the heat flux H and horizontal wind speed, u. The following algorithm is assumed: $\sigma_u^2 = 0.3w_*^2 + 6.25u_*^2$ for small heights z. See text for explanation of other variables.

u (m s^{-1})	H (W m^{-2})								
—	0	5	10	20	50	100	150	200	250
0.0	0	0.319	0.402	0.507	0.688	0.867	0.992	1.09	1.176
0.5	0.073	0.336	0.419	0.522	0.701	0.879	1.005	1.104	1.187
1.0	0.145	0.366	0.444	0.545	0.722	0.899	1.02	1.12	1.205
1.5	0.218	0.404	0.478	0.575	0.748	0.921	1.04	1.14	1.225
2.0	0.290	0.448	0.518	0.610	0.778	0.948	1.07	1.166	1.248

In these light wind conditions, it can be seen that σ_u is most sensitive to the heat flux. In fact $\sigma_u \approx 0.187H^{1/3}$ when u is small.

In stable conditions, as long as there is some wind, it seems that σ_u is governed by low frequency meanderings and shallow gravity flows, to the extent that a quasi-minimum value is reached independent of the mean wind speed. This has been noted by Hanna and by others. Hanna (1983) has reported measurements of plume widths from low-level upwind sources, sampled over an hour, one at Oak Ridge, Tennessee, and the other at Idaho Falls. The measurements, reproduced in Fig. 1, are stated to be broadly consistent with a crosswind σ_u of about 0.5 m s^{-1}. However, when looked at rather more closely, the fit is less convincing at each site taken in isolation; at Oak Ridge, as Fig. 2 shows, a better fit is obtained by assuming the angular width of the plume 100 m downwind from the source is given by $\sigma_\theta = 0.3/u$. At Idaho Falls, the fit to any simple relationship is far from convincing, as shown in Fig. 3.

The data on the fluctuations in wind directions over 3-minute sampling periods, reported by Smith and Abbott (1961), are given in Fig. 4. These data are subdivided according to a measure of stability s. On the stable side, an inverse relationship with wind speed is evident, in an averaged sense. The equivalent crosswind value of σ_u is about 0.26 m s^{-1}. This implies a value of about 0.35 m s^{-1} if the sampling period were to be extended to one hour.

1.2 Instruments are inadequate

From a purely practical point of view, it may be argued that a good definition of low wind-speed criterion is provided by the speed when the wind-measuring instruments begin to perform inadequately.

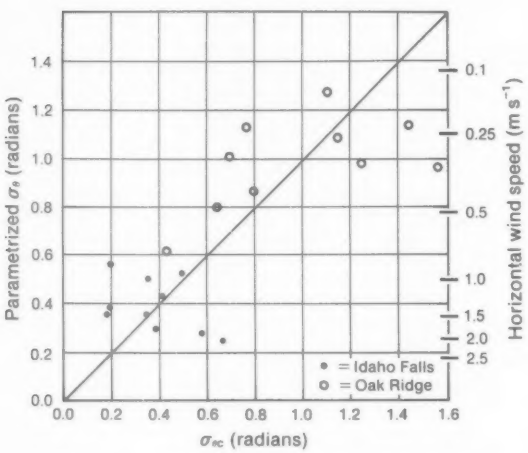

Figure 1. Observations of standard deviation of crosswind distribution of material in plume divided by distance from source ($\sigma_{\theta c}$) determined from the concentration distribution, compared with parametrized $\sigma_\theta = \tan^{-1}(0.5 \text{ m s}^{-1}/u)$ based on wind observations.

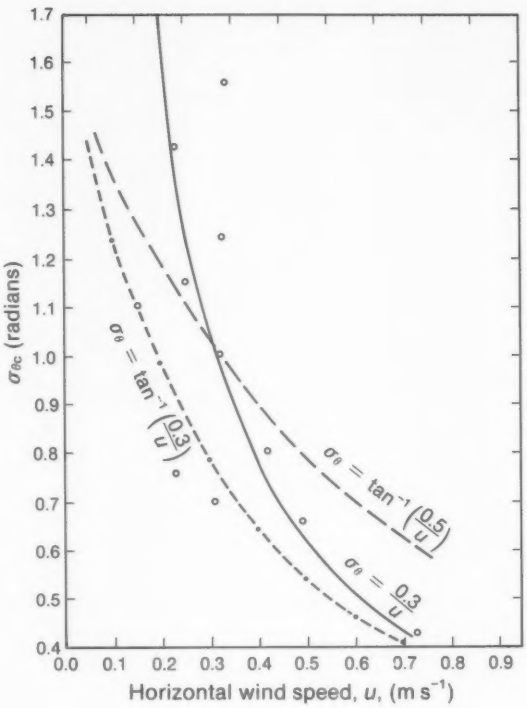

Figure 2. A replot of the Oak Ridge data from Fig. 1 (1-hour averages for stable light-wind cases) showing that the assumption that $\sigma_u = 0.5$ m s^{-1} is not a particularly good fit.

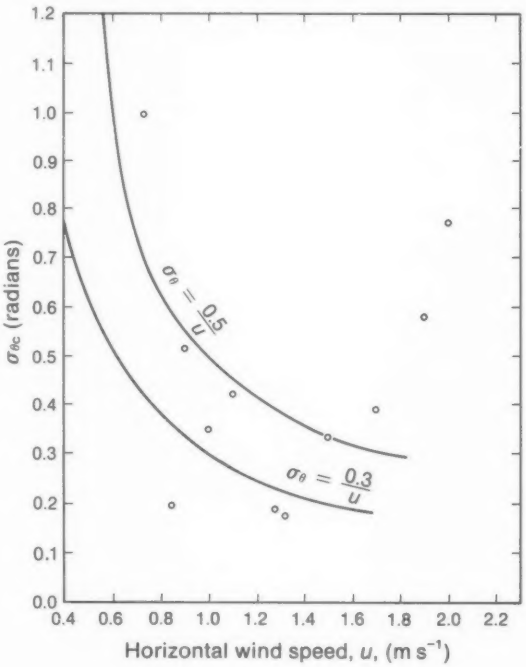

Figure 3. As Fig. 2 but for Idaho Falls data.

This however makes the speed a function of the instruments. Table II shows the recording errors of standard vanes and anemometers; it is clear their performances are not very good for pollution purposes when the winds are light. In particular the cup anemometers can only be trusted when the wind speed is greater than about 6 knots, or 3 m s^{-1}. Such instruments are designed to be very robust in all sorts of extreme weather conditions, and to record accurately conditions that are important to weather forecasting, and to the

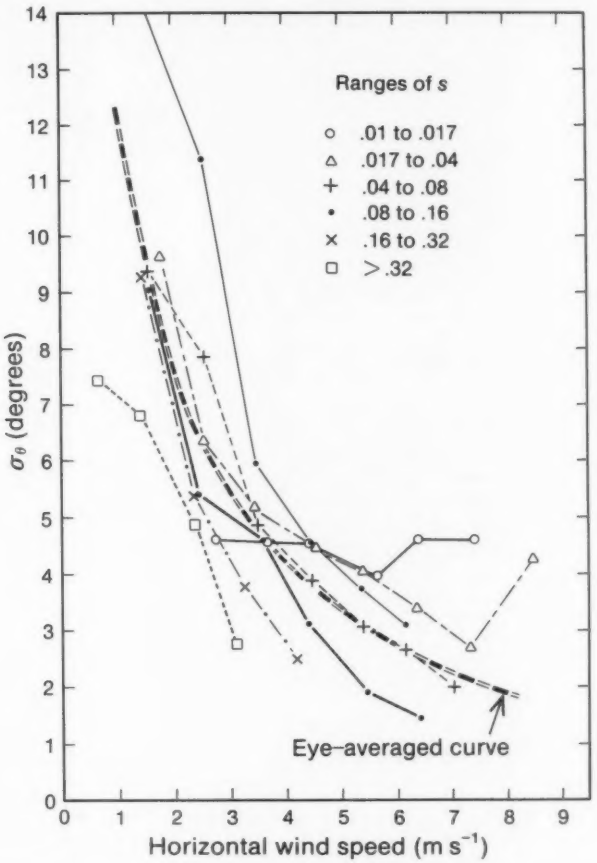

Figure 4. Fluctuations in wind direction (σ_θ) for various ranges of measures of stability (s) over 3-minute sampling periods, from Smith and Abbott (1961). The stability parameter s was defined as $(T_{7.1\text{ m}} - T_{1.2\text{ m}})/u^2_{15.5\text{ m}}$. The eye-fit curve is close to $\sigma_\theta = 15/u$, implying $\sigma_\theta = 1.26$ m s^{-1} for 3-minute samples.

Table II. The standard procedure for assessing wind speeds by Meteorological Office observers. Instrument movements are assessed over the 10 minutes prior to the observation.

Anemometer	No movement	No movement	Occasional movement	Movement
Wind wave	No movement	Some movement	Some movement	Movement
Classed as:	Calm	2 kn	3 kn	4 kn or above as indicated

Standard instrument and recording errors:
Wind direction (vanes): starting speed 1–2 kn, direction recorded to nearest 10°.
Wind speed (anemometers): cups on standard instruments start to rotate when speed > 4–6 kn.

safety of the public. This they do well. However there is obviously a need for more sensitive instruments for pollution purposes. Anemometers of the 'Porton' type are good examples and many automatic weather stations now on the market are equipped with one of these. Wind speeds can be measured accurately down to 1 knot. Unfortunately, although there are believed to be over 200 of these in operation around the United Kingdom, the great majority are privately owned and are not connected up to any network where the results are available to other potential users. Ideally, what is required is for a network of such improved instruments to be installed and maintained by some authority with pollution responsibilities at sites across the country where pollution episodes are most probable.

Unfortunately with the standard instruments commonly used the wind speed has to be subjectively assessed at low values using the procedure set out in Table II. Inevitably this must introduce some error.

1.3 Topographical control greater than geostrophic control

A third possible criterion could arise from consideration of the relative importance of geostrophic and topographical controls over the motion of the air. In light winds the geostrophic control becomes weak, and the influence of slopes, hills and valleys and coastlines becomes relatively more important. Theoretical and experimental studies would be required in any locality to establish some sensible criterion for that locality.

2. Measurement problems

2.1 Representativeness

Most releases, whether they be continuous or accidental, usually occur some distance away from where meteorological data are available. In applying algorithms or models to predict the likely consequences, the best meteorological data are required. Wind direction is probably the most important of all these data since this determines whether or not any potential receptor is likely to be affected by the plume. In interpolating the winds from neighbouring meteorological stations to the site, or from instruments on the site of the emission to points in the plume at various distances downwind, the danger of introducing significant errors is all too clear.

Fig. 5 shows the location of six meteorological observing stations in the United Kingdom. Four of these are lowland inland stations, Blackpool Airport is an exposed coastal site and Eskdalemuir is in the Scottish Southern Uplands at an altitude of 242 m above sea level.

Hourly values of wind direction (which are recorded to the nearest 10°) have been compared between all the stations whenever the wind speed at Wyton was less than 5 knots or, separately, greater than 20 knots. The station separations range from 55 km (between Watnall and Finningley) and 370 km (between Wyton and Eskdalemuir). For Wyton wind speed less than 5 knots the r.m.s. wind direction difference increases sharply with range from under 35° at 55 km to 63° at 370 km in January and February, 1990. The results are plotted in Fig. 6. Although there is scatter, the points above the dashed lines contain all the points involving Blackpool, the site most influenced by a major topographical feature — a coastline.

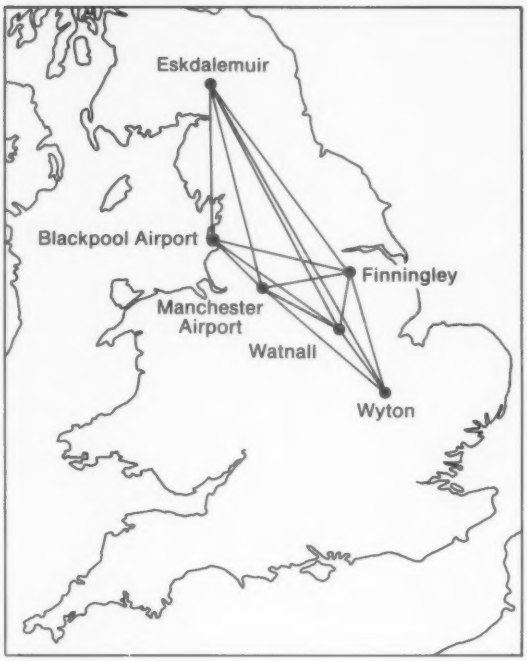

Figure 5. The locations of the six stations used in the study of wind differences as a function of station separation.

The implied values of σ_θ for the low wind speeds are significantly larger than those for the high wind speed class plotted on the same figure. This implies, of course, that at low wind speeds the geostrophic control becomes less and topographical influences are more important. It may also imply that the geostrophic wind itself is more spatially variable in situations of light winds. Fig. 7 compares the r.m.s. differences for light winds for June with those for Jan.–Feb. 1990. It shows that the June values tend to be significantly larger by some 20°. This is probably due to the generally weaker and more variable synoptic winds in June compared to the winter adding an extra factor to the effect of nocturnal surface inversions creating light low-level winds.

A similar study has been made by Lockhart and Irwin (1981) on the St Louis RAPS data. Here the station separations were on a rather smaller scale ranging from 0.1 to 80 km. The values are given in Table III and are

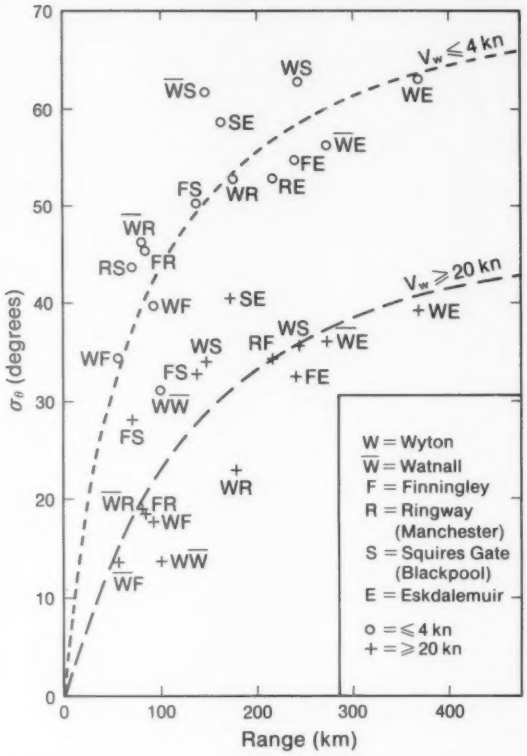

Figure 6. A comparison of r.m.s. wind-direction differences with range between six sites in the United Kingdom for Jan.–Feb. 1990. See Fig. 5 for station locations and text for an explanation of layout.

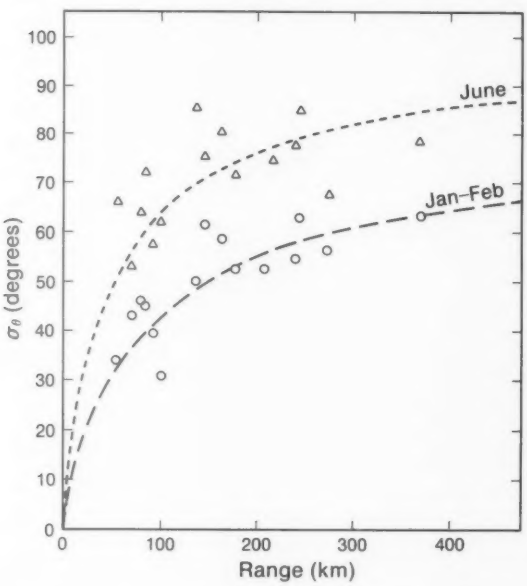

Figure 7. A comparison of r.m.s. wind direction differences in June and Jan.–Feb. 1990 for light winds at Wyton (occurring mainly at night) with distance separation between sites. See Fig. 6 and text for explanation of symbols.

Table III. Root-mean-square differences in hourly wind speed (u) and direction (θ) from 25 stations (with separations between 3 and 80 km) within the St Louis network as a function of distance, using high-quality instruments. The following empirical formulae appear to represent these values: $\sigma(u_a - u_b) = 0.47 + 0.24 \ln(x)$ and $\sigma(\theta_a - \theta_b) = 15 + 5.7 \ln(x)$. The constant first terms on the right-hand side of the two formulae could be larger if less accurate instruments were to be employed.

Separation (x (km))	$\sigma(u_a - u_b)$ (m s^{-1})	$\sigma(\theta_a - \theta_b)$ (°)
0.1	—	2
0.5	0.3	11
1.0	0.5	15
2.0	0.64	19
5.0	0.86	24
10	1.02	28
20	1.2	32
40	1.4	36

broadly consistent with the values and curves shown in Figs 6 and 7. Fig. 8 show the RAPS values plotted against wind speed for stable, neutral and unstable conditions. The values from all combinations from the 25 stations are grouped together, and the curves show that the r.m.s. differences in both direction and speed increase significantly as the wind speed becomes small.

2.2 Accuracy in low winds

The problems in accuracy of measurement have already been touched on earlier, and won't be repeated. As we saw, the accuracy depends very much on the instruments being used, and the recent improvements point to a gradual improvement in general accuracy in the future.

2.3 Surrounding topography and roughness length (z_0) changes

Almost all stations are influenced to a greater or lesser degree by the inhomogeneous nature of the terrain surrounding the site and its instruments. At most stations, the wind profile suggests an increase in effective roughness length with height, so that in neutral conditions for example the profile is not logarithmic as predicted by theory. In light winds, especially at night in stable conditions, the wind profile may be strongly influenced by a wide variety of features stretching up to many kilometres upwind. An example of this will be seen later when we compare the statistics of light winds at Eskdalemuir with those at other stations.

3. Frequency of occurrence and persistence

3.1 Time-of-day occurrence

Inspection of records of wind speed at observing

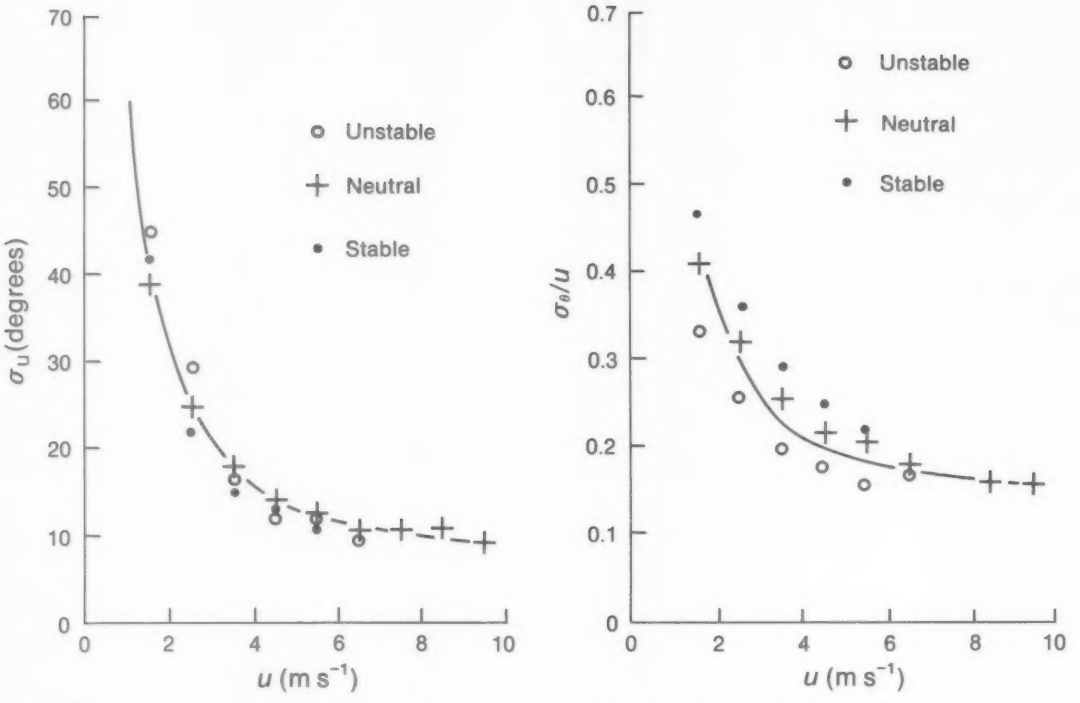

Figure 8. Variation of spatial σ_u and σ_u/u with wind speed and stability for hourly St Louis data. The spatial standard deviations are calculated from concurrent observations at 25 monitoring stations. Empirical equations are also drawn on the figures: $\sigma_u^2 = (5°)^2 + (60°/u)^2$ and $(\sigma_u/u)^2 = (0.15)^2 + (0.6/u)^2$.

stations reveals, as expected, that the majority of light-wind cases occur at night with clear skies or broken cloud, when the lower boundary layer becomes stably stratified. This is particularly true whenever the surrounding terrain has sufficient trees, or other large obstacles, to extract momentum from these lower layers to leave almost windless conditions below the height of the obstacles. Immediately above, a rather turbulent jet tends to exist, which may be only a few metres deep, with a more quiescent airflow above. Cases of daytime calm or light winds tend to occur in the centre of large regions of high pressure in winter or summer (although in the latter, convectively driven motions may give a semblance of a mean light wind).

Data from Finningley are fairly representative of the diurnal cycle. The four months of January, February, June and July, 1990, have been analysed in terms of time of day. The results are shown in Fig. 9. The size of the sample is small and may have introduced unrepresentative aspects of detail, but the general trends are probably correct. It can be seen that calms are a feature of night-time and the early morning, with no cases occurring in the sample from 11 to 19 UTC. Light winds, recorded as 2 knots, show a marked maximum between midnight and 09 UTC with a smaller maximum around 18 UTC and two minima around 14 and 20 UTC. The curves for slightly higher wind speeds (3 knots and 4 knots) show a much more uniform diurnal distibution with, however, a minimum around 18 UTC and a maximum around 22 UTC.

3.2 Monthly occurrence

Fig. 10 gives an example from Ringway (Manchester Airport) of the month-to-month variation in the percentage frequencies of light winds with speeds less than or equal to 3 knots. The figure shows not only the mean monthly frequencies, but also the year-to-year r.m.s. variations in the mean and the extreme values over a 10-year period from 1981 to 1990. The figure also shows that the period from January to March tends to have the fewest light-wind hours, with the greatest number occurring in November, and the season with the greatest number being summer.

Fig. 11 shows the percentage probability of the hourly averaged wind being less than any specified value calculated from data collected during the four months January, February, June and July, 1990. It implies an almost constant probability of the speed lying in any fixed speed band out to about 4 knots.

Fig. 12 shows the percentage number of hours with the wind speed less than or equal to 3 knots, by month, averaged over the same six stations used earlier. As at Ringway, the winter period shows the least number with the greatest number during the summer months and in November.

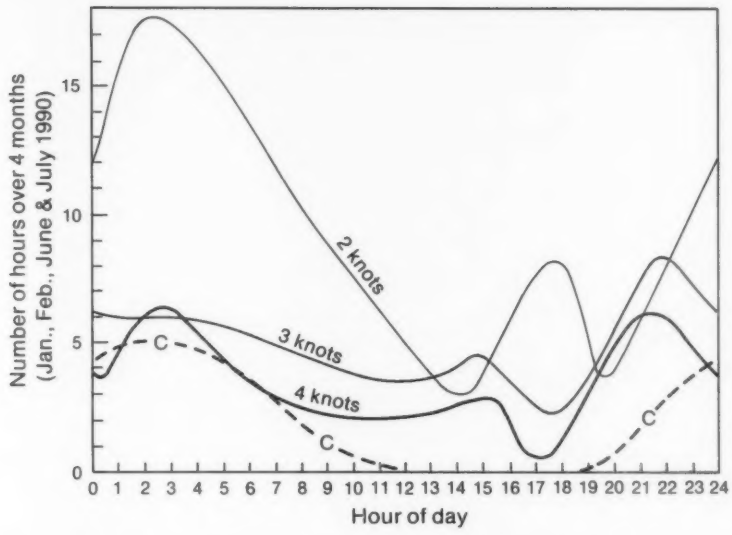

Figure 9. The diurnal cycles of light-wind frequencies (C = calms) at Finningley during the four months shown.

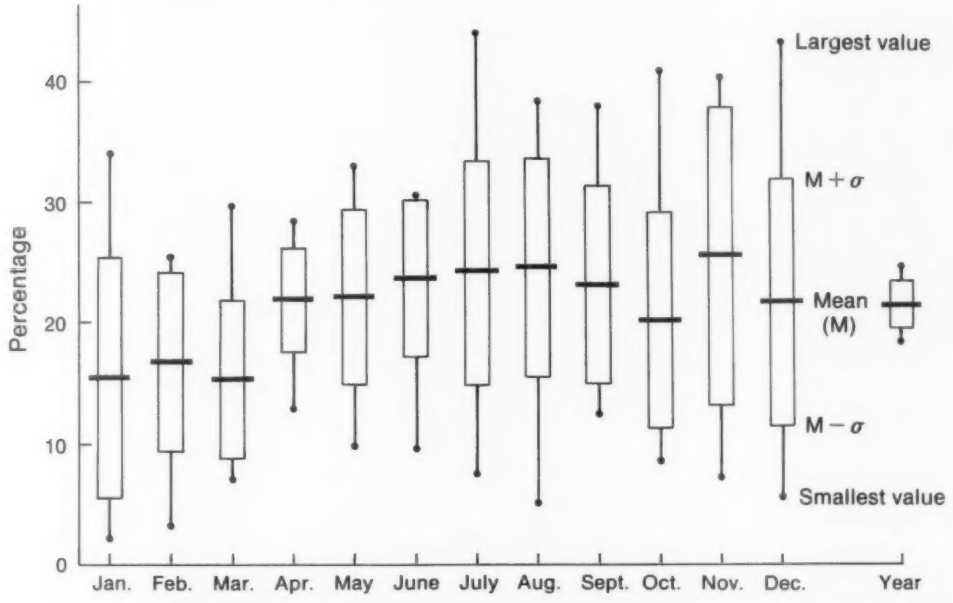

Figure 10. The percentage mean-monthly frequencies of winds ≤ 3 knots at Manchester Airport over the 10 years from 1981 to 1990. A measure of the variation is also included.

3.3 Location occurrence

Table IV gives value of percentage frequencies of hours when the wind speed at 10 metres was less than 4 knots at the same six stations, divided accorded to month. Table V gives the annual figures averaged over the 10 years from 1981 to 1990. It comments on the large frequencies found at Eskdalemuir where it seems that the influence of higher hills within several kilometres of the site causes significant sheltering whenever the gradient wind is fairly light. At first it was thought that the sheltering may have been due rather more to the surrounding forests, but this seems to be unlikely since a comparison of comparable statistics for the decade 1961–70 shows relatively small differences even though the conifers were much smaller at that time. Such differences as are evident can easily be explained by: natural decade-to-decade variations, and a change during the mid 1960s to a better anemometer at Eskdalemuir. Overall the table shows that the frequency

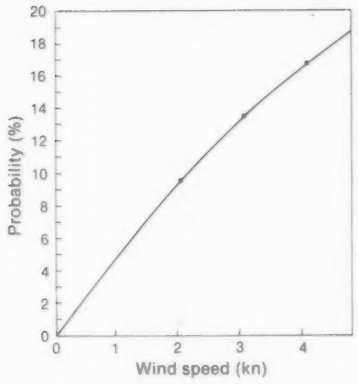

Figure 11. Percentage probability of the hourly 10 m wind lying below a specified value at Manchester Airport during the same months as in Fig. 9.

of light winds varies quite markedly between sites, and this must provide a warning that simple interpolation to any potential emission site has to be carried out with considerable care taking into account all the factors involved.

3.4 Persistence

The persistence of light-wind situations is revealed from an analysis of hourly data from the inland lowland site at Ringway. Fig. 13 shows the cumulative percentage probabilities that the wind speed is less than or equal to 2, 3 or 4 knots for any specified number of consecutive hours. Between 40 and 60% of cases last for one hour only, but beyond that the probability distribution is consistent with a Guassian or Normal distribution, giving straight lines on the graph. Thus there is a 10% probability that given one hour of wind speed 2 knots or

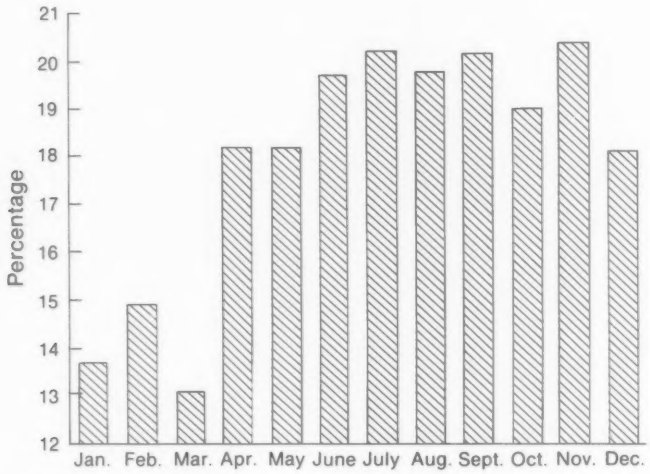

Figure 12. Percentage number of hours with wind speed ≤ 3 knots averaged over the six stations of Fig. 5 for the 10-year period from 1981 to 1990.

Table IV. Percentage frequencies of hours when the wind speed at 10 m was less than 4 knots at six stations in the United Kingdom, divided according to month

Month	Watnall	Ringway	Squires Gate	Finningley	Eskdalemuir	Wyton
Jan.	11.2	15.5	7.6	13.1	25.9	8.9
Feb.	11.6	16.8	6.7	17.1	27.1	10.1
Mar.	12.1	15.3	7.5	13.0	22.8	7.8
Apr.	15.0	21.8	11.2	18.7	30.5	12.0
May	15.2	22.0	9.8	18.7	29.2	14.3
June	18.4	23.5	9.6	20.8	30.8	15.3
July	19.1	24.0	8.8	21.8	32.2	15.0
Aug.	19.2	24.4	9.6	21.9	28.3	15.2
Sept.	19.0	23.0	10.1	20.8	32.5	15.8
Oct.	18.2	20.0	9.4	21.5	30.4	14.7
Nov.	17.4	25.3	11.0	19.8	33.6	15.2
Dec.	14.1	21.5	9.7	16.8	32.5	11.1
Year	15.8	21.1	9.2	18.7	29.7	13.0

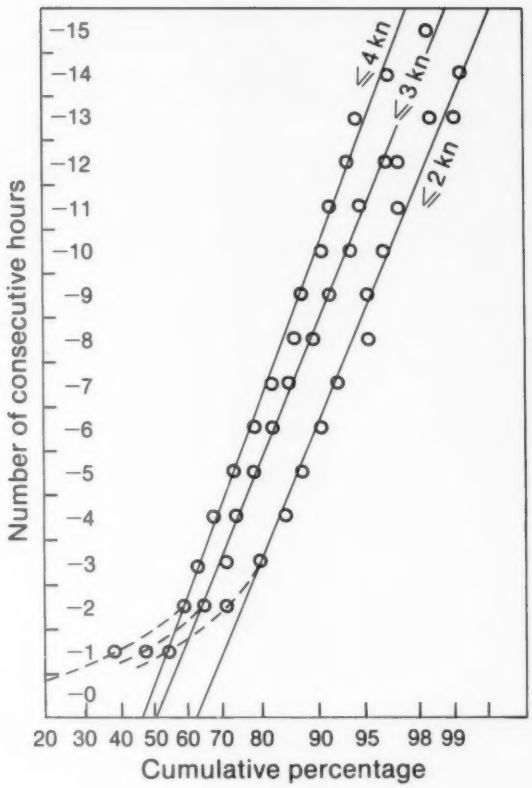

Figure 13. Persistence of light winds at Ringway, e.g. 90% of runs with wind ⩽ 2 knots last 6 hours or less, and 7% of all runs with wind ⩽ 2 knots last between 6 and 10 hours.

less, the speed will persist in this band for six consecutive hours or more.

4. Relation between surface and upper winds

Rossby Similarity Theory predicts that, over a very uniform and extensive terrain in rather stationary conditions, the surface wind and the geostrophic wind should be related as functions of Kazanski–Monin Stability parameter μ (which includes the heat flux), the surface roughness z_0, and the Coriolis parameter f. Arya (1975) provided empirical forms for this relationship, but as his data showed, considerable scatter is apparent, in part due to the lack of ideal conditions almost always prevailing (see Fig. 14).

The same sort of scatter is apparent in Fig. 15, which shows a comparison of the ratio V_{10}/V_{1000} plotted against the 1000 m wind V_{1000}. The 10 m wind was taken from a surface-based anemometer, and the 1000 m wind from radiosonde data, both originating from Crawley (Gatwick) in Surrey. The results are subdivided according to time of day: 00, 06, 12 and 18 UTC. All show considerable scatter and no obvious systematic varation with V_{1000}. At night the average value of the ratio is about 0.23 with most points lying within ±0.10 of that value. At 06 UTC the scatter is even more extreme with no obvious division according to estimated sensible heat flux at the ground. Conditions are clearly too transitional to provide any guide to the magnitude of the ratio.

At 12 UTC, the amount of scatter is still very large with no certain division according to estimated heat flux, although there is a suggestion that the average value of the ratio is somewhat higher (0.63) in clearly

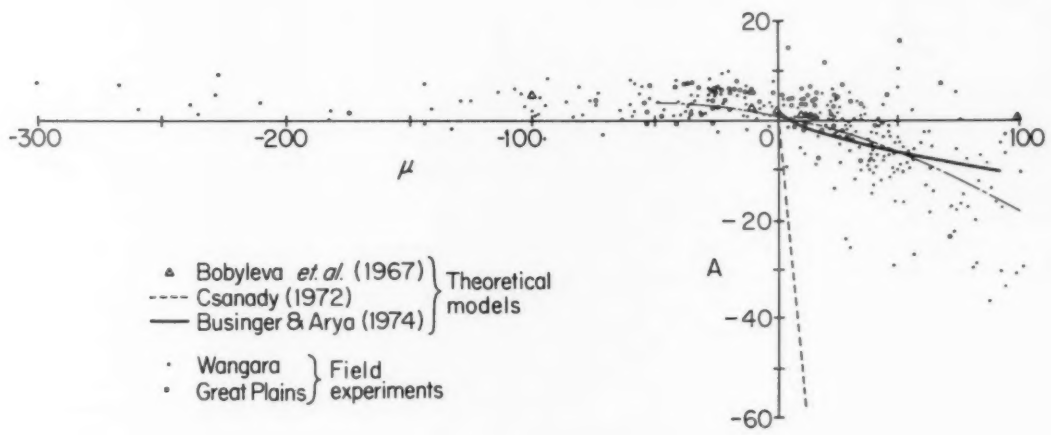

Figure 14. The form of one of the parameters in Rossby Similarity Theory, showing the amount of data scatter.

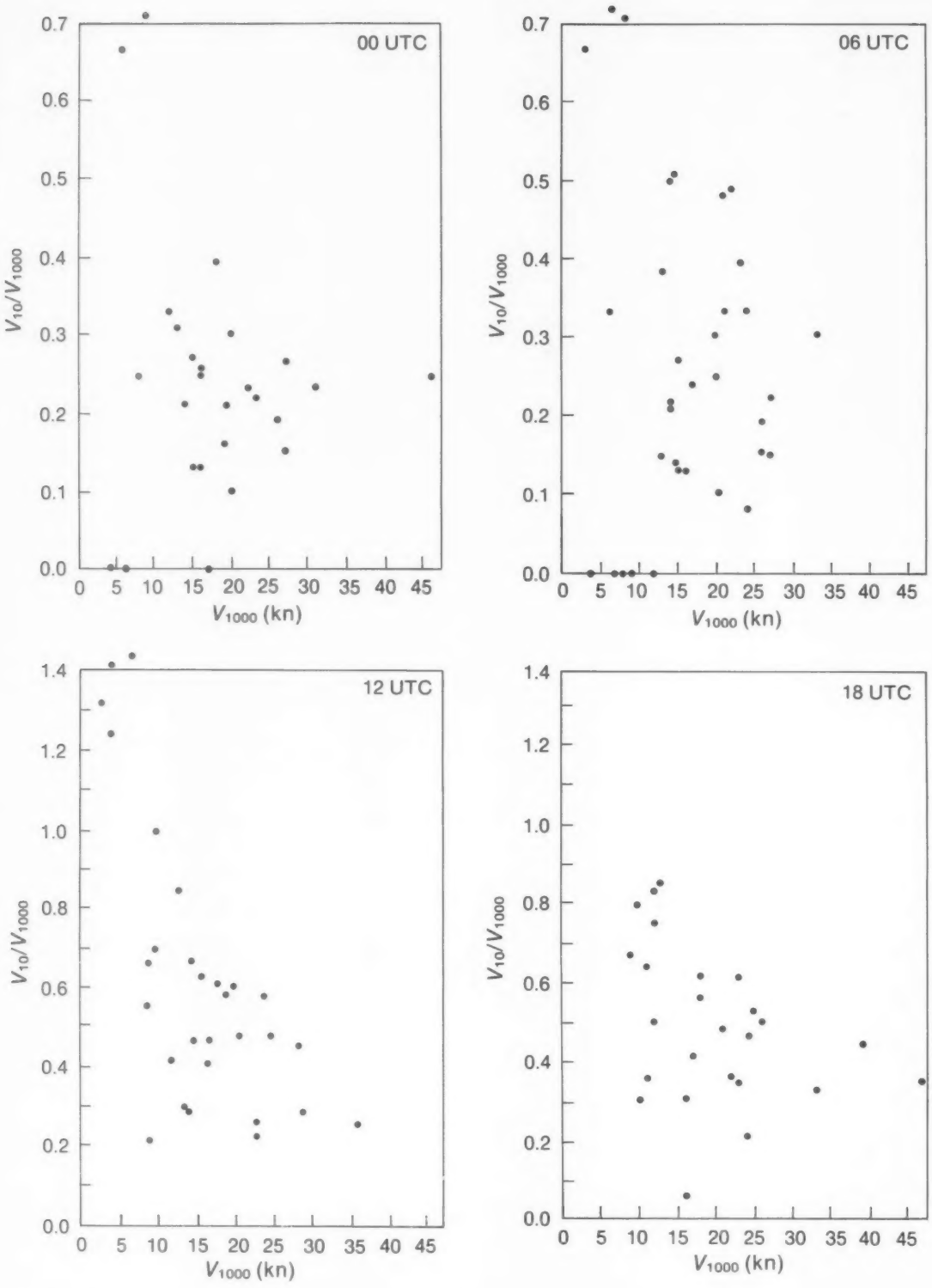

Figure 15. A comparison of the ratio V_{10}/V_{1000} plotted against the 1000 m wind, V_{1000}, at the times shown for Gatwick during June 1990.

Table V. Percentage frequencies of hours of calms and light winds over the 10-year period 1981–90, for the six stations in Table IV

Station	Calms	< 4 kn
	Percentages	
Watnall	1.4	15.8
Ringway	2.3	21.1
Squires Gate	0.6	9.2
Finningley	2.7	18.7
Eskdalemuir	6.6	29.7
Wyton	2.0	13.0

Note. The frequencies for Eskdalemuir are somewhat surprisingly large for a station 242 m above mean-sea-level in the Scottish Uplands. The area around the site is largely forested except to the north. It is in a slight hollow on the shoulder of a valley running north–south. At a range of a few miles it is surrounded by higher hills. It seems that the hills provide sufficient sheltering to produce very low 10 m winds when the gradient winds are fairly light. From a directional analysis of these light-wind cases (often at night) it seems that the anemometer is often being affected by northerly gravitational flows.

unstable conditions, than in near neutral conditions (0.46). There is perhaps also an increase in the scatter at lower wind speeds which implies that Rossby Similarity Theory is on even more shaky ground at low speeds.

At 18 UTC, the scatter is slightly less with a mean value of the ratio again lying somewhat near 0.46 (with most points lying within 0.26 of the mean) apparently appropriate to near neutral conditions.

Similar studies, concentrating on higher wind speeds and on coastal sites, are reported in the *Handbook of Weather Forecasting* produced by the Meteorological Office, and come to similar conclusions.

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Incident above Zanjan

R.W. Lunnon*
Meteorological Office

At 2347 UTC on 29 November 1989, a British Airways Boeing 747 was near the town of Zanjan (Fig. 1) in the Zagros mountains while *en route* from Bahrain to London. Suddenly the aircraft pitched up, lost air speed, and fell from flight level (FL350 (238 mb, approximately 35 000 ft)) to FL260 (360 mb, approximately 26 000 ft). The pilot was so disconcerted by this occurrence (understandably!) that he issued a 'mayday' call. However, at FL260 he managed to level off and the flight continued to London.

The nearest radiosounding was from Lenkoran (WMO number 37985) on the south-west coast of the Caspian Sea. Fig. 2 shows it has almost neutral static stability from 210 mb (FL390) down to 425 mb (FL220) at potential temperature of 47 °C; in conjunction with the fairly light winds at low levels this would seem to rule out classical mountain waves.

The infrared image from Meteosat at the time of the incident is shown at Fig. 3, with coastlines and the approximate track of the aircraft shown, ending at the location of the incident. The topography of this region is dominated by ridges running from south-east to north-west with valley bottoms at about 1500 m and ridge tops at 2500 m — this is shown in Fig. 1. The spacing between the ridges is about the same as that of the lines convection apparent in Fig. 4, an enlargement of the area of interest. It is believed that the incident was caused by convection whose scale and orientation were determined by orographic effects. It is considered that the aircraft encountered a downdraught associated with the convection and that this caused the 9000 ft height loss. The wind at the time and location was south-westerly at 60 knots, which is roughly perpendicular to the ridges and convective lines.

It is not known how common this type of occurrence is. What are believed to be classical mountain waves are seen quite frequently in satellite imagery, but it is rare for a check to be made on the stability to establish the true cause. It is worth noting that downdraughts are inherently more dangerous than updraughts, partly because they cause aircraft to accelerate downwards, and partly because they are not usually marked by cloud or precipitation and are therefore invisible. Downdraughts at high level should be apparent on water-vapour imagery as dry zones, as was the case here. It would probably be worth inspecting water-vapour imagery in the vicinity of mountains for evidence of mountain wave activity in cloud-free conditions for this particular threat to aircraft safety.

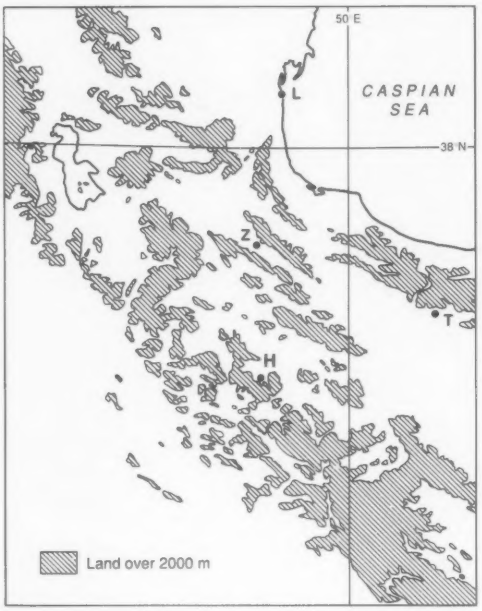

Figure 1. Map of the area of the incident showing the south-east to north-west orientation of the ridges. Z is Zanjan; L is Lenkoran; T is Tehran; H is Hamadan.

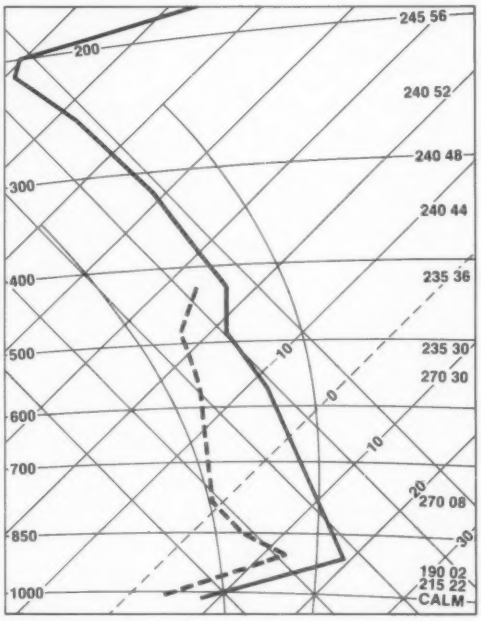

Figure 2. Tephigram for Lenkoran 0000 UTC on 30 November 1989 showing near-static stability between 210 mb and 425 mb. Pressures in mb, wind speeds in knots and temperatures (°C).

* The preliminary investigation of this incident was carried out by Dr D.A. Forrester and K. Grant.

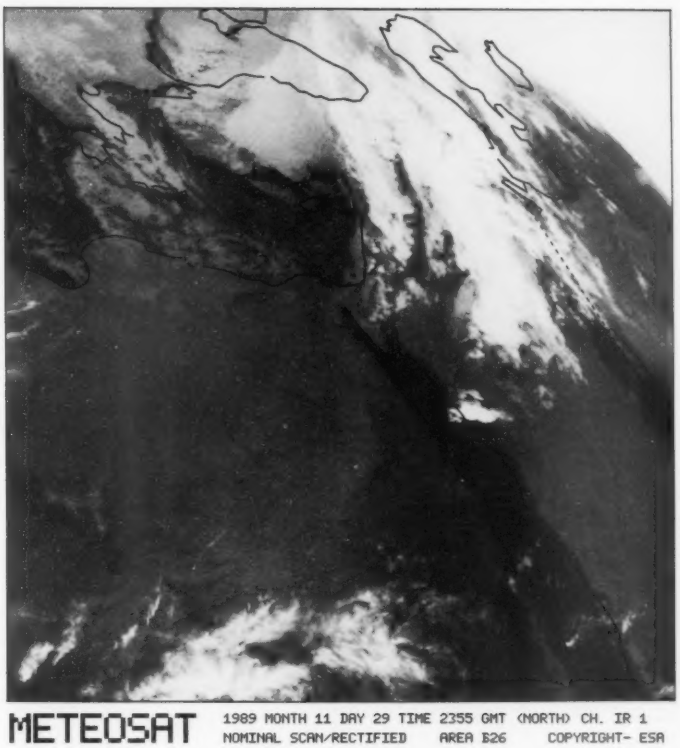

Figure 3. Meteosat infrared image around the time of the incident showing the flight path from Bahrain to Zanjan.

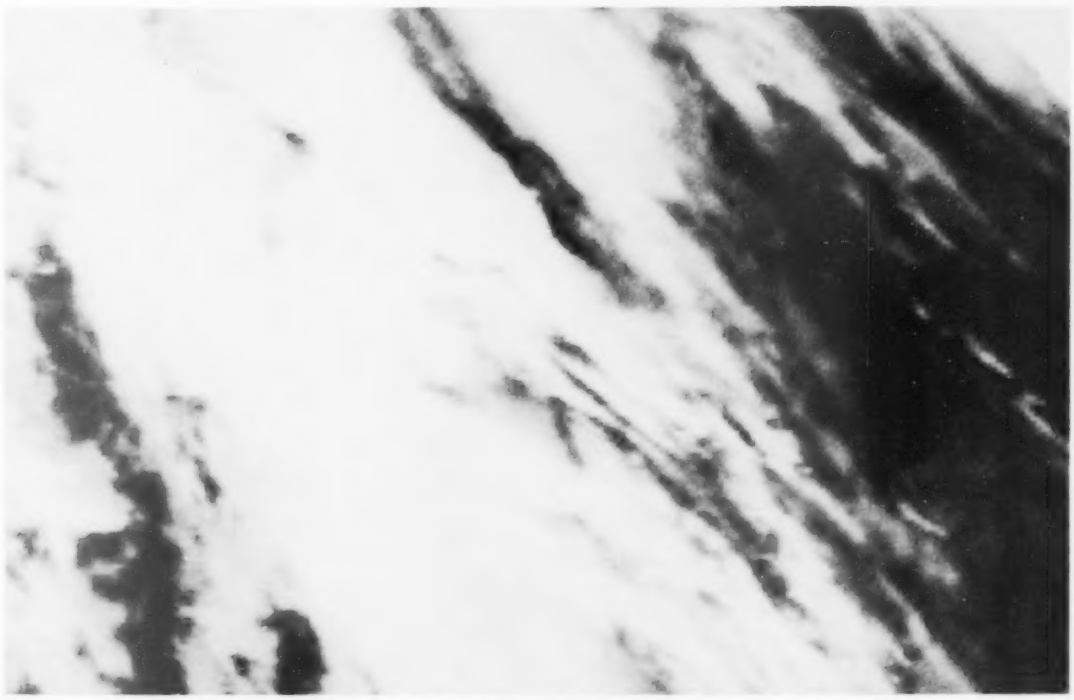

Figure 4. This is an enlargement of part of Fig. 3 showing clear-cut straight edges to the clouds in the area of the incident.

Reviews

Theoretical geophysical fluid dynamics, by A.S. Monin. 165 mm × 246 mm, pp. xii+399, *illus.* Dordrecht, Boston, London, Kluwer Academic Publishers, 1990. Price £99.00, $149.00. ISBN 0 7923 0426 8.

In this ambitious monograph based on a lecture course delivered at the Moscow Institute of Physics and Technology, Professor Monin presents a valiant attempt to cover an astonishing range of topics in the study of the dynamics of some geophysical fluids, namely the Earth's liquid core where the geomagnetic field originates, the mantle of the Earth, the oceans, and the lower atmosphere. With the exception of the mantle, which behaves like a highly viscous fluid when subjected to long-term forcing (but like an elastic solid at seismic frequencies), Coriolis forces due to the Earth's general rotation relative to an inertial frame exert a dominant dynamical influence on large-scale flows. Buoyancy forces associated with stable (i.e. bottom-heavy) density stratification are also dynamically important in the cases of the atmosphere and oceans; Lorentz forces associated with electric currents and concomitant magnetic fields are dynamically important in the liquid core. Professor Monin is one of a very small number of scientists who have studied the dynamics of all these regions of the Earth, and his book amounts to a personal (not always up-to-date) view of his areas of interest.

General concepts and basic dynamical processes are treated in the first two sections of the book, which deal with the basic equations of geophysical fluid dynamics, the theory of small amplitude oscillations in rotating stratified fluids, including oscillations of an isothermal atmosphere and Rossby waves, baroclinic and other types of instability, and turbulent flows. A fluid is often thought of as differing from a solid through its inability to support shear (vorticity) waves. Rotation, stable density stratification or, in the case of electrically conducting fluids, magnetic fields, bestow a quasi-rigidity to the fluid which enables disturbances to propagate over large distances through the agency of shear waves, which in general are both dispersive and anisotropic. Finite amplitude effects can give rise to soliton-type behaviour. In many cases the waves are generated by internal instabilities (e.g. baroclinic instability associated with horizontal density gradients) or interactions with irregular boundaries.

Applications are treated in the final section of the book, with chapters on the general circulation of the atmosphere and ocean, theory of climate, and the dynamics of the Earth's core and mantle. As in previous sections, for reasons that are by no means clear, the references cited in the text are not always up-to-date and many do not appear in the reference list at the end of the book. These and other shortcomings in the editing of the monograph make it hard for this reviewer to give more than a qualified recommendation to this interesting and wide-ranging discussion of geophysical fluid dynamics by one of its most distinguished practitioners.

R. Hide

History of the Commission for Agricultural Meteorology of the World Meteorological Organization, prepared by W. Baier, I.G. Gringof, N.D. Strommen. 205 mm × 292 mm, pp. x+197, *illus.* Geneva, WMO, 1991. WMO/TD No. 440.

At the 1987 Commission for Agricultural Meteorology (CAgM) Meeting in Madrid delegates approved the appointment of a Task Force to write a history of CAgM. The result is a very readable book packed with vital information about the work done by CAgM and those who have contributed to its success.

The book comprises four chapters and a series of annexes. To quote from Dr Baier's preface 'Chapter 1 presents an introduction to the historical development of the Commission within the International Meteorological Organization and the World Meteorological Organization. Chapter 2 looks at the early history and development of IMO and the Commission for Agricultural Meteorology. Chapter 3 deals with the transition of IMO to WMO, the formation of CAgM and its relationship to other technical bodies of WMO and to the Regional and international organizations. Chapter 4 forms the main body of the report. It describes the development of CAgM from the first to the ninth session, primarily from the viewpoint of policy, plans and goals including terms of reference, collaboration with other WMO bodies and with other national and international agencies.'

There are nine Annexes to the report. They include a Who's Who of all those who have ever served the Commission including rapporteurs, delegates, observers and members of the Secretariat — it is a long list running from page 79 to page 155. Details of all the CAgM Sessions are given in Annex 2, together with a list of the resolutions, recommendations and appointments made by each session. There are also lists of WMO and WCP publications related to the activities of CAgM and a list of the published proceedings of seminars, training courses and technical conferences sponsored by CAgM or attended by WMO. Annex 8 gives a brief chronology of relevant events from the First International Meteorological Conference, Brussels in 1853 up to the Fourth Norbert Gerbier Mumm Award in 1990.

As already indicated the heart of the book is chapter 4 — it gives readers abbreviated biographies of the six

presidents and describes the progress made by CAgM under the individual presidencies.

In the early period under Burgos (Argentine) and Bourke (Ireland), the role and limits of agrometeorology were examined; attempts to merge the Commission with the Commission for Climatology were successfully resisted and the terms of reference of the Commission more rigorously defined; technical regulations were devised and co-operation with international organizations was established and set on a firm footing. Among the topics of special interest studied during the latter part of this period were forestry, tropical agrometeorology, and locust control.

The presidencies of Smith (United Kingdom) and Baier (Canada), spanning the years from 1967 to 1974, were a time during which there were increasingly prolonged periods of drought in many areas of the world and major food shortages. The problems were exacerbated by the massive rises in oil prices which affected the economies of both developing and developed countries all over the world. As a result of these pressures there was a major change in direction of the Commission's work, from data gathering to solving urgent operational problems such as the role of meteorology in the protection of the environment and natural resources, how agrometeorology could aid world food production and how relevant technologies could be transferred to developing countries. It was during this period that the World Weather Watch programme was devised and the CAgM was able to advise on, among other matters, the information required for the monitoring of global food production from weather data.

During this period two innovations were made that are still operational today, namely the setting up of an Advisory Working Group (AWG) and the system of appointing Rapporteurs.

The AWG is a small select group of experts appointed by the Commission to assist the President with various statutory duties and to assist with urgent unforeseen business arising between sessions. This was necessary because of the greatly increased workloads faced by the presidency during L.P. Smith's time.

Prior to this period the technical work of the Commission had been handled by working groups but financial restrictions on the Commission now meant that only ten could be sustained at any one time. During an era when giant strides were being made in new technologies this was seen to be a serious problem. The solution hit upon was to appoint Rapporteurs, i.e. acknowledged experts in particular fields who were willing, voluntarily and freely, to undertake specific investigations, for the benefit of CAgM, and to provide written reports for CAgM, to be issued later as WMO publications.

The most recent period considered by the Task Force covers the years from 1974 to 1986 under the presidencies of Baier, Gerbier (France) and Kassar (Tunisia). The critical food shortages of the early years were eventually turned into food mountains in some countries, largely due to improved agricultural practices and new technologies but also improved global weather conditions. The 5th President, Norbert Gerbier (who died in October 1985), pointed out that in 1982, while overall world food production looked good it had in fact fallen in 33 of the 69 developing countries, with significant losses being caused by pests and diseases and thus there was considerable scope for agrometeorology to play a decisive role in minimizing losses and increasing production.

These recent years have very busy ones for the Commission, both technically and administratively, and it was particularly pleasing for the Commission to see their roving seminars, fellowship schemes and their training missions to 55 countries, bear fruit in the form of an increased involvement of developing countries in the Commission's affairs.

There is a note on page ii that this book has been produced without editorial revision by the WMO Secretariat and it comes as no surprise to find a number of small, irritating typographical errors — for instance, did the first meeting of Directors of European Meteorological Services really take place in 1735 as indicated on page 2? The new Chairman of CAgM, Professor C. Stigter, has no doubt noticed that his name has been misspelt on page 180 (but not on pages 143 or 189). The readability of the book would have been improved significantly if the three periods described above had been treated as separate chapters, or if the various subsection headings had been emphasized differently.

The Task Force have produced a most interesting book which deserves a wide readership. It will be of particular value to CAgM delegates both old and new; the latter will find it very useful for reference purposes — the Who's Who Annex especially. It will also be welcomed by those interested in the history and development of agrometeorology, though they will not be able to identify contributions made by individual countries. Bearing in mind that these Commissions do have political influence, they will perhaps find clues as to why particular policies were followed at particular times. They will also find this book a very good complement to the descriptive history of CAgM given in Sir Arthur Davies' book *40 Years of Progress and Achievement: a Historical review of WMO.*

Finally it is worth noting that the recent CAgM meeting urged Members to produce histories of their own agrometeorological services as a way of increasing awareness of the value of agrometeorology. We can already look forward with anticipation to the histories, soon to be published, of the Canadian and Chinese agrometeorological services.

P. Harker

Air traffic and the environment — Background, tendencies and potential global atmospheric effects, edited by U. Schumann. 165 mm × 241 mm, pp. vi+170, *illus*. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1990. ISBN 3 540 53352 4.

This slim review of the potential environmental impacts of air traffic can be broken down into three main sections: the nature and extent of aircraft emissions, potential chemical impacts leading to changes in radiatively active trace species and perturbations to the distribution of water vapour and cirrus clouds.

These notes start off by considering the geographic extent and likely magnitude of aircraft emissions, noting that the number of passenger miles is set to increase significantly over the next decade and that some of that increase will be above the more remote areas of the planet than is presently the case. Chapters 3 and 4 stay on the emissions theme and consider new hydrogen technology and the likely improvements in efficiency and reductions in emissions which may accrue from improvements to conventional engines.

The bulk of the fuel burnt in an aircraft engine is converted into carbon dioxide and water vapour, with much smaller quantities of nitrogen oxides, carbon monoxide and unburnt hydrocarbons. Chapter 5 reviews the background composition of the upper troposphere and lower stratosphere and tries to put the magnitude of aircraft emission into a relevant atmospheric context by assessing the likely perturbation to the background concentrations for a given, highly idealized, emission and dispersion scenario. From this analysis it is concluded that the aircraft emissions most likely to influence background distributions significantly are water vapour and nitrogen oxides. Chapters 6 and 7 describe the results from 2-D and 1-D model runs respectively, both employing emission scenarios which include a major growth in the number of high-speed civil transports (HSCT) flying in the mid-stratosphere. These studies conclude that if there is a major increase in HSCT and at the same time we manage to reduce the chlorine loadings from CFCs, then NO_x from HSCT may become the dominant anthropogenic sink of stratospheric ozone.

In addition to the chemical impacts which ozone may have in the stratosphere, the emission of large quantities of water vapour into a part of the atmosphere which is close to saturation may promote a change in the frequency of cirrus clouds. Chapters 8 and 10 considers the climate impacts from increased incidences of contrails and from extra water vapour generally, while chapter 9 considers methods for determining contrail coverage globally from space.

In the preface Schumann points out that the papers on which this document is based were gathered together prior to a 2-day seminar and there was little time to revise or edit those papers before publication. He asks that the deficiencies which arise from this approach be excused because of the more 'precise information' (perhaps he means more up to date?) and the early publication of the results. While it is clear that some of the material could have been improved had more time been taken, I am inclined to side with Schumann. While this will never be a classic text, it should provide a useful source document for scientists who are interested in the potential impact that aircraft emissions may have in the atmosphere.

Where this document is likely to be deficient is that it is directed in large part at the potential impacts of a fleet of high flying HSCT which may never be built, while not considering as fully the impact of the assured growth in conventional air traffic which could have dramatic impacts on the ozone and water budgets adjacent to the tropopause.

D.S. McKenna

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Climate, data and resources: A reference and guide, by E. Linacre (London, Routledge, 1992. £50.00 (hardback, £16.99 (paperback)) focuses especially on the sorts of observation which are made at a single climate station. Also included are modern-day methods of parametrization of surface conditions for computer modelling and interpretation of satellite observations. ISBN 0 415 05702 7 (hardback), 0 415 05703 5 (paperback).

Seasonal snowpacks: Processes of compositional change, edited by T.D. Davies, M. Tranter and H.G. Jones (Berlin, Heidelberg, New York), 1991. DM 288.00 (hardback)) contains the papers presented at the NATO Advanced Research Workshop held at Maratea, Italy, 23–27 July 1990. Biological, chemical and physical aspects of the subject are considered. ISBN 3 540 51760 X.

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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Editorial Board: R.J. Allam, R. Kershaw, W.H. Moores, P.R.S. Salter, J. Gloster

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